

## C + G Joint Session - FFAG + Cyclotrons.

Conveners: Schmelzbeck, Mori, Dutta, Baastman

- |                                     |                                   |
|-------------------------------------|-----------------------------------|
| 1. PSI cyclotron                    | Schmelzbeck                       |
| 2. High Intensity cyclotrons at IBA | Jongen                            |
| 3. Isochronous + Scaling FFAGs      | Baastman                          |
| 4. FFAG development at KEK          | Mori                              |
| 5. Beam Dyn. in FFAG                | Aiba                              |
| 6, 7, 8. FFAG for $\nu$ -factory    | Johnstone<br>Koscielnicki<br>Berg |
| 9. Stochastic Cooling in FFAG       | Wakasugi                          |

~ 25 attendees

## Summary of session G (Cyclotrons)

\* Cyclotrons are high intensity accelerators

### J. Jongen (IBA)

- ① - many low-energy cyclotrons of the "cyclone" series deliver routinely 10 mA beams for isotope production
- ② - self-extraction works. 80-90% efficiency demonstrated so far.
- ③ - development of a 350 MeV, 5 mA cyclotron for HYRRHA. Principle: acceleration of  $H_2^+$  to 700 MeV,  $H_2^+ \rightarrow 2 H^+$  by stripping in C-Foil.  
#② ≠ ③ Solve the problem of beam trips due to arcing in the electrostatic extractors!

### P. Schmelzbach (PSI)

- ① PSI-Ring Cyclotron: Iohō's rule ( $I_{sc\ limit} \propto E^{3/2}_{gain}$ ) verified between 200 - 2000 μA (@ 590 MeV)  
→ reasonable extrapolation to a 1 GeV, 10 mA machine.
- ② PSI-Injector 2 : uses longitudinal sc effect + strong bunching to achieve small phase width.
- ③ extraction efficiency for both machines: 99,98%

## Beam matching at high beam intensities PSI Inj.2

- longitudinal space charge effects are strong in cyclotrons, and radial and longitudinal motion are strongly coupled

⇒ at high currents the beam has to be matched in 6 dimensions

⇒ circular bunch is a stable configuration under space charge

- simulation

PSI Inj.2,

1.5mA

contours lines

10,20,50,80%

(Adam 1985)

$n = 15, R = 1265\text{mm}$

$R \uparrow$        $n = 10, R = 1033\text{mm}$

how SC helps (!) to form  
"round" bunches with  
narrow phase widths.

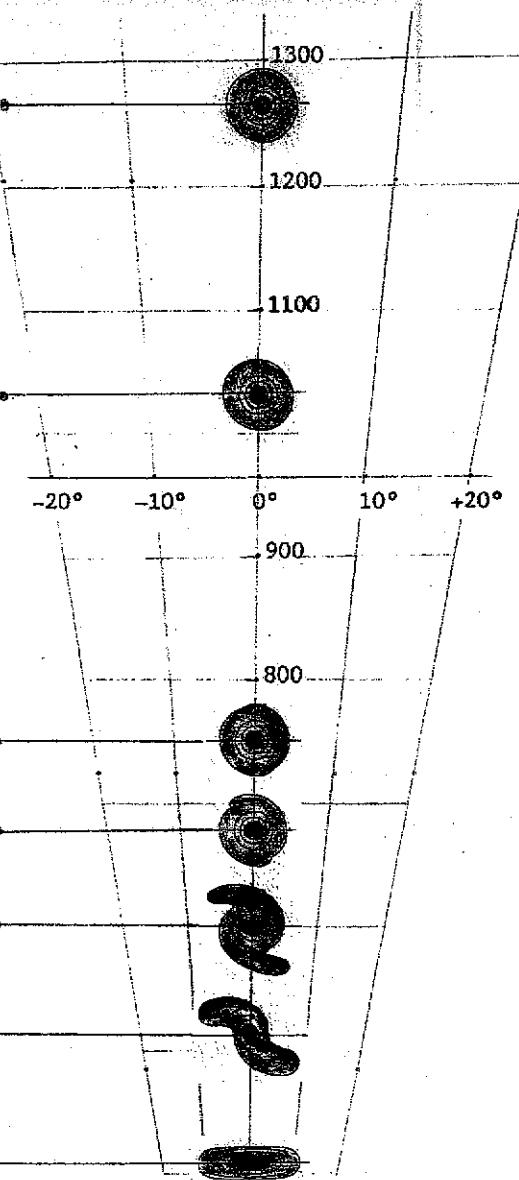
$n = 5, R = 747\text{mm}$

$n = 4, R = 678\text{mm}$

$n = 3, R = 600\text{mm}$

$n = 2, R = 513\text{mm}$

$n = 1, R = 406\text{mm}$



- note:

- a circular bunch in radius and phase is stable under acceleration,
- $dR = d\phi = \pm 6\text{mm}$  corresponds to 17 deg fw at injection
- phase width becomes extremely narrow at extraction (~2deg)
- a slightly mismatched bunch is captured into the matched phase space (Adam, Koscelniak, PAC 1993)

When are cyclotrons an appropriate choice?

Ans: For  $E$  up to about 1 GeV, Power up to 10 MW

Why 1 GeV?

$$(\gamma = \gamma_+, v_x \approx \gamma_+)$$



Isochronism demands  $v_x = \gamma$ . So  $\gamma \gg 1$  would require crossing many resonances. E.g. to avoid intrinsic  $v_x = N/3$  requires # of sectors  $N > 3 \gamma_+$ .

Why  $\bar{I} \lesssim 10 \text{ mA}$ ?

Space charge fattens beam bunches, making clean extraction difficult because turns overlap. OTOTL, bunches are extremely short at the space charge limit,  $\sim 100 \text{ ps}$ . (Recall  $\gamma = \gamma_+$ )

However, if beam must be pulsed, as for a spallation neutron source, linacs are better.

'New' kid on the block: FFAG synchro-cyclotron.

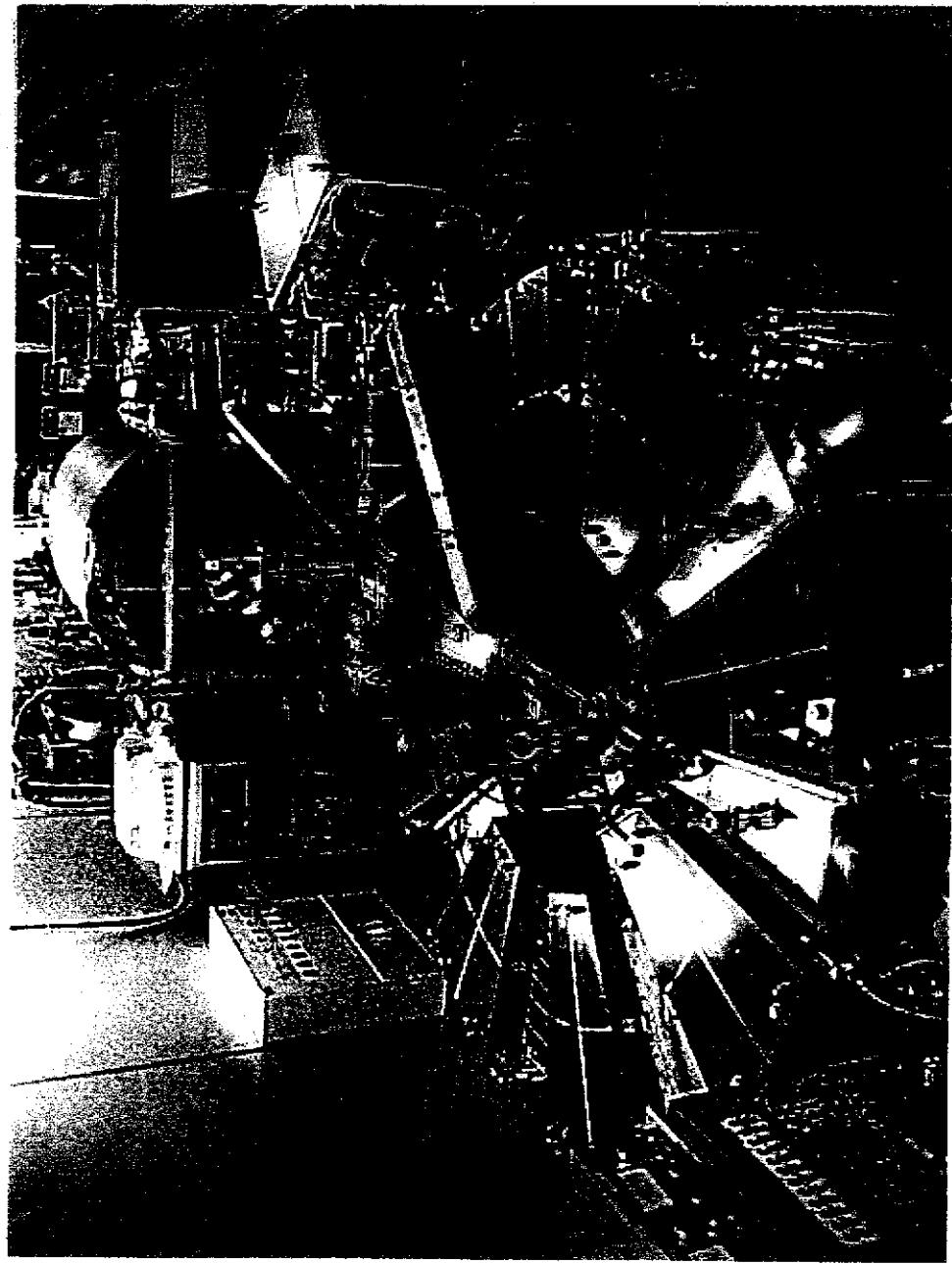
(actually, first proposed by G. L. Smith, 1955,  
but they didn't want to name it after him)

What we now usually call FFAG's are scaling FFAG's, which have the feature that though the orbit grows with  $E$ , tunes are constant. But since this cannot be isochronous, beam must be pulsed, rf frequency must be ramped, but  $B$  is dc.

Invented 50 years ago, the Japanese group under Y. Mori's direction revived the idea by inventing a new type of rf cavity: one which uses magnetic alloy instead of ferrite (or mechanical). This makes rapid acceleration, rapid frequency ramping feasible.

The standard model is now a "magnetic dipole" or "barrel-shaped" cyclotron. FFAGs, a decade away today, can be built in a 1.5 GeV FFAG for cancer treatment.

# *Pop proton FFAG model*



FFAGs have 2 market niches:

- ① If we want high power, high energy ( $\sim 10\text{GeV}$ ) and do not mind high rep rate ( $\sim 1\text{kHz}$ ), they are likely cheaper than either ~~linacs~~ or synchrotrons.
- ② If we need to rapidly accelerate secondary particles (e.g. muons), which have ~~the~~ short lifetime and large emittance,  $\Delta\eta/\rho$ , they are probably the best choice.

This is because scaling FFAGs have enormous acceptance: up to  $10,000 \pi\text{ mm-mad}$ ,  $100\% \Delta\eta/\rho$ . (as demonstrated in R-P machine)

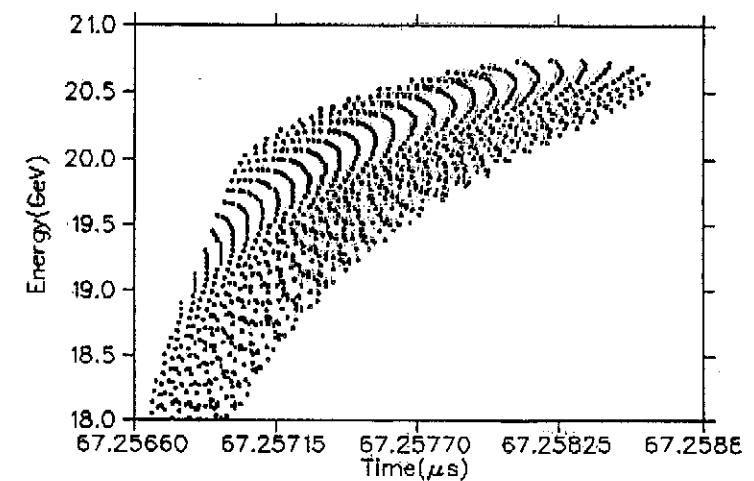
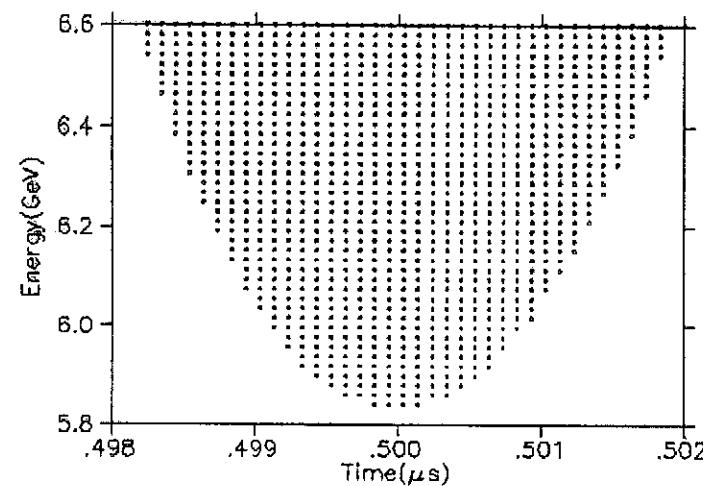
There were 4 talks on FFAG's not related to high-brightness hadron beams, but rather to secondary beams.

Shane Koscielniak, Carol Johnstone, Scott Berg are working on FFAG for muon acceleration. FFAG's are much better than re-circulating linacs because of their much larger acceptance.

However, because of short  $\mu$  lifetime, it is desirable to accelerate to  $\sim 20\text{GeV}$  in  $\sim 1\text{ms}$ . This requires very high rf voltage,  $\Rightarrow$  High Q cavities  $\Rightarrow$  Constant freq. BUT, FFAG cannot be made isochronous or the large acceptance is lost. Compromis: Make FFAG "somewhat isochronous" and accelerate so rapidly that the phase slip can be tolerated.

Simulations were presented for 5-10 turn,  $6 \rightarrow 20\text{GeV}$  FFAG. By carefully arranging the phases of the different cavities, acceleration was demonstrated. Simulations with transverse motion included are still to be done.

# 10-turn, 100 MHz Acceleration--Output Longitudinal Phase Space



Input phase space with +/- 10% band (left) and output phase space for Best Phases and 30% overvoltage (right)

(RIKEN)

Lastly, Wakasugi<sup>↙</sup> presented another cool idea:  
For a Radioactive Isotope (RI) beam factory,  
use a cyclotron - FFAG combination to capture  
the (cw) RI beam, convert to a pulsed beam,  
stochastically cool inside the FFAG, & load  
into the RI collider ring.

Initial 3D cooling simulations were presented.